

# 複雑系数理モデルに基づく断裂型地熱貯留層における物質・熱移動挙動のキャラクタリゼーションと工学応用に関する研究

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学位論文題目	複雑系数理モデルに基づく断裂型地熱貯留層における物質・熱移動挙動のキャラクター化と工学応用に関する研究 Characterization of mass/heat transfer in fractured geothermal reservoirs by means of complex system mathematical model and its engineering applications
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## 論文内容要旨

Reinjection prevents a decline in pressure and an exhaustion of water in a geothermal reservoir. One of the major problems with this process, however, is the possibility of an early thermal breakthrough in the production well. Tracer testing is a standard method for tracing mass transport, and is a valuable tool in the design and management of production and injection operations. This study focuses on the tracer analysis in order to evaluate the effect of reinjection on reservoir performance in fractured reservoirs.

The objective of this dissertation is to develop a new mass and heat transfer model of complex systems based on fractional derivatives. The fractional Advection-Dispersion Equation (fADE) characterizes mass transport in a highly complex fractured system by using fractional derivatives. This dissertation proposes two approaches of tracer analyzes based on the fADE as shown in Fig. 1.

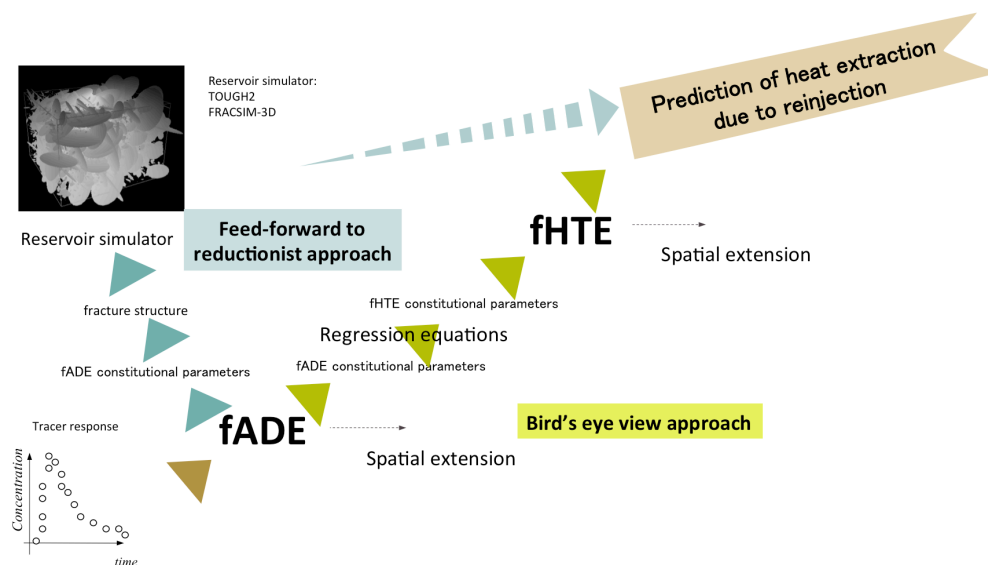


Fig.1: Prediction of thermal response due to reinjection based on a tracer response.

## fADE

fractional advection-dispersion equation

$$\frac{\partial C}{\partial \tau} + b_3 \frac{\partial^\gamma C}{\partial \tau^\gamma} + b_1 \frac{\partial^\beta C}{\partial \tau^\beta} = \frac{1}{Pe} \frac{\partial}{\partial X} \left( p \frac{\partial^\alpha C}{\partial X^\alpha} + (1-p) \frac{\partial^\alpha C}{\partial (-X)^\alpha} \right) - \frac{\partial C}{\partial X}$$

i ii iii iv v

## fHTE

fractional heat transfer equation

$$\frac{\partial T}{\partial \tau} + e_3 \frac{\partial^\gamma T}{\partial \tau^\gamma} + e_1 \frac{\partial^\beta T}{\partial \tau^\beta} = - \frac{\phi_2 \rho_w C_{pw}}{\rho_2 C_{p2}} \frac{\partial T}{\partial X}$$

i ii iii iv

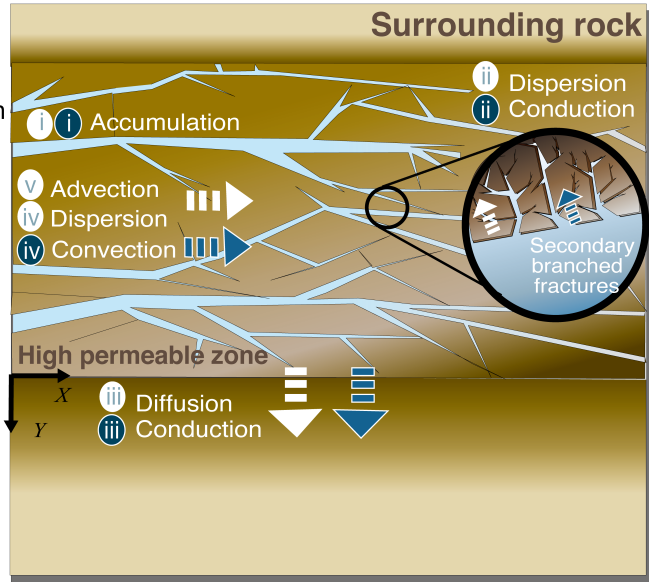


Fig. 2: Schematic of a fractured reservoir and the governing equations of the fADE and the fHTE.

Chapter 2 introduces the derivation of the governing equation in the fADE and represents the numerical method for solutions of the governing equation. The mathematical theory in the fADE is related to the fracture structures observed from geothermal reservoirs. The frequency distribution histograms of fractures in the Rapolano geothermal area show that the fracture densities are highly constant around the vicinity of the fault core and decrease with the distance on the outside from the area. The decay in the fracture densities is fit by a power law approximation. Therefore, the results suggest the diffusion process into the surrounding rocks can be described by using fractal diffusion equation. The diffusion equation with fractional derivatives expresses the diffusion from fractures into matrix due to secondary branched fractures. In addition, the dispersion in the highly permeable zone is described by using non-Fickian flux, which includes spatial fractional derivatives. The governing equation in the fADE is written in Fig. 2. This dissertation discusses the two types of reservoirs characterized by the fADE. One reservoir takes into account only penetration into the surrounding rocks, which is expressed by the third term on the left-hand side in the fADE. The reservoir is referred to as Reservoir-I. Another reservoir is considered only interaction between fractures and matrix within the reservoir. The effect of diffusion into matrix due to secondary branched fractures is expressed by the second term on the left-hand side, and the heterogeneity of fracture distributions is described by the first term on the right-hand side in the fADE. The reservoir is referred to as Reservoir-II. Additionally, a numerical method of a finite difference algorithm for solving the fADE is presented. Comparison with the analytical solutions confirms the reliability of the algorithm.

In Chapter 3, numerical simulations of fractured reservoirs provide quantitative analyses of the relationship between the fADE constitutional parameters and the fracture structures in fractured reservoirs. This investigation offers new insight into the feed-forward to reductionist approaches. Tracer behaviors observed in the reservoir-I and the reservoir-II are validated. For the Reservoir-I, a simulation model adjusting permeability distributions for a fault zone is implemented in the general geothermal simulator TOUGH2. The fault zone consists of highly permeable zone and the surrounding rocks where the permeability decreased with the distance from the highly permeable zone according a power law. An increase in the permeability of the surrounding rocks leads to a gradual decrease of the concentration in the tracer response curve, whereas tracer response for a constant permeability of the surrounding rocks exhibits a secondary peak. Conventional advection–dispersion models describes tracer responses only when the surrounding rocks were impermeable. In contrast, the fADE solution is found to be in reasonable agreement with the tracer response for the fault zone model. The Reservoir-II is simulated by using a fracture network model (FRACSIM-3D) and an equivalent continuum model (MINC) that discretizes the matrix block into smaller units. In the FRACSIM-3D, either low fracture density or fracture distribution considering fractal of fracture lengths causes heterogeneous distributions of the permeability and then results in long tails in tracer responses. Besides, in the MINC, wider fracture spacing causes a heavier tailing in the tracer response. The results from both models

shows the fADE characterized the tracer responses obtained from the reservoirs including mass exchange between fractures and matrix. The fADE constitutional parameters depend on the fracture parameters constituted in reservoir simulators, such as the degree of permeability of the surrounding rocks in the fault zone model, fractal dimension in the FRACSIM-3D, and fracture spacing in the MINC. Linear regression analyses were conducted to provide predictive equations of the constitutional parameters in the reservoir simulators. Therefore, the fADE constitutional parameters obtained from tracer response are expected to be effective and objective indicators that estimate fracture structures for a conventional reductionist approach.

A bird's eye view approach for prediction of thermal response due to reinjection is discussed from Chapter 4 to Chapter 6.

Chapter 4 summarizes a spatial extension of the fADE. The effects of different flow patterns on prediction of tracer responses is investigated by using the FRACSIM-3D. For one-dimensional flow, the fADE solution shows reasonable agreement with the tracer data at short distance (100 m). In addition, the fitting parameters at spacing of 100 m can be used to make predictions at the longer spacings (up to 400 m) where the tracer response includes a long tail. Subsequently, in the case of interwell flow, the tracer analysis requires a consideration of a change in the Peclet number in the fADE since the flow velocity changes with well spacings. Prediction of a tracer response for a natural stream depends on the fracture distribution in the fracture network model. The relationship between the well spacings and the maximum size of distributed fractures is also validated. A fracture network model including longer fractures than the observation intervals causes the scale dependent of the dispersivity. The fADE constitutional parameters may not have reached the convergence values in the case where the scale for characterizing the heterogeneous hydraulic property distribution is longer than the observation spacing, and then the fADE has limitations on prediction irrespective of differing well intervals.

Chapter 5 explains a proposed heat transfer model and the validity of the model to characterize thermal response in fractured reservoirs. A diffusive analogy between mass and heat transfer is used to derive a new fractional heat transfer equation (fhTE) as described in Fig. 2. This equation is linked with the fADE by normalization with the peak time in the tracer response. Synthetic numerical results and field data is used for validation of the applicability of the fhTE to characterize thermal responses in fractured reservoirs as separating the reservoir types. For the Reservoir-I, the fault zone model is used to generate a temperature profile caused by cold-water injection with penetration into the surrounding rocks. The temperature profile depends on the degree of the penetration. Conventional intergranular model (Bodvarsson, 1972) represents thermal breakthrough in the case where the surrounding rocks are impermeable. In the case, variable transformation (Shook, 2001) also applies to prediction of the temperature changes. Fick's diffusion model (Gringarten and Sauty, 1975) shows better agreement with the temperature profiles when the surrounding rocks are more permeable. The solutions of the fhTE are in good agreement with the calculated temperature profiles irrespective of the degree of the penetration. Subsequently, the Reservoir II is simulated by using the MINC and, interaction between fracture and matrix are evaluated. The temperature profiles for wide and narrow fracture spacings are characterized by the intergranular model and Fick's diffusion model, respectively. The fhTE expresses the temperature changes from the wide spacing to the narrow spacing. Therefore, it suggests the fhTE is an intermediate model between intergranular model and Fick's diffusion model. The variable transformation model is unstable for the MINC results. The temperature decline observed from Balcova geothermal field is fit by the fhTE solution for the reservoir-I. The fhTE shows a significant improvement for thermal response analysis in fractured reservoirs.

Chapter 6 proposes a prediction of thermal response based on a tracer response. The relationships of constitutional parameters of the fADE and the fhTE with the fracture structures are evaluated. The constitutional parameters in the Reservoir-I are obtained by using the fault zone model in Chapter 3 and Chapter 5. The fhTE constitutional parameters show the same dependence of the degree of penetration into the surrounding rocks as the fADE constitutional parameters. In this case, both mass and heat transfer behaviors are controlled by penetration of water. Regression equations to estimate fhTE constitutional parameters based on the fADE constitutional parameters are obtained as follows:

$$e_1 = -0.12\beta + 0.17b_1 + 0.25 \quad (1)$$

$$\beta' = 0.15\beta + 0.10b_1 + 0.34 \quad (2)$$

Synthetic numerical results are used to evaluate the estimation accuracy of the regression equations. The fADE constitutional parameters determined by a tracer response are substituted into the regression equations, and the regression equations generate the predicted values of the fhTE constitutional parameters. The predicted results based on the fhTE constitutional parameters shows good agreement with the temperature profile simulated by TOUGH2. The correlation coefficients expressing the

prediction accuracy are greater than 0.99 regardless of the degree of penetration into the surrounding rocks. Furthermore, by using the tracer response at a short well spacing (100 m), the temperature profile at a long well spacing (200 m) is successfully predicted. Hence, the fADE and the fHTE are expected to offer a simple prediction method of thermal responses in fractured reservoirs.

Finally, the two approaches proposed in this dissertation are summarized. The bird's eye view approach based on the fADE and the fHTE is to predict thermal extraction due to reinjection. Since this approach requires only a tracer response and operation conditions, such as well pressure and injected temperature, it is expected to be a powerful tool in the case where we obtain only inadequate field data. The second proposed approach is to predict thermal extraction by feed-forward to the conventional reductionist approach. By estimation of the fracture parameters in general reservoir simulators, the method is expected to increase in efficiency and improve objectivity in a reservoir analysis. The fADE and the fHTE characterize mass and heat transfer in a fractured reservoir. Therefore, it can be applied to a general development in a fractured reservoir, such as carbon capture and storage (CCS) and high-level waste disposal. Furthermore, it is possible that the analysis method based on the fADE and the fHTE are extended to characterization of mass and heat transfer in complex systems and its application over study fields.

論文審査結果の要旨及びその担当者

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論文審査結果の要旨

地熱貯留層の代表的なタイプである断裂型貯留層は、複雑な分布を有する天然あるいは人工き裂を含む岩体であり、地熱開発においては複雑き裂システムにおける物質・熱移動を評価・予測することが必須の課題となる。このためには、複雑き裂システムの局所的地下情報に関する詳細を記述する手法も重要である一方、貯留層の全体的な物質・熱移動を俯瞰的に特徴づける方法の開発も時間的および経済的観点から有効であることが期待される。本論文は、複雑系の数学的表現である非整数階微分を活用し、断裂型地熱貯留層における物質・熱移動挙動を特徴づける方法論に関する検討を行い、それらの結果をまとめたもので全編7章よりなる。

第1章は緒論であり、本研究の背景を述べている。

第2章では、地熱貯留層の天然き裂分布および構造をモデル化し、非整数階微分に基づく移流分散方程式 (fADE) と地熱水の散逸挙動との関係について検討することにより fADE モデルにおける物理的意義を与えている。さらに fADE モデルに基づき断裂型貯留層を対象とした物質移動数値シミュレーションコードを構成し、種々の貯留層条件でトレーサ応答挙動を解析するとともに理論的結果との比較により解析コードの妥当性を検証している。

第3章では、第2章のき裂分布・構造に関するモデル化に基づき、地熱貯留層を2つのタイプ、すなわち均質透水層と指数関数的にき裂密度が減少する逸水領域とからなる貯留層モデルおよび不浸透層ではさまれた複雑き裂を有する不均質貯留層に分類し、それぞれの貯留層モデルに対して、fADE モデルを構成する微分の階数などからなる fADE 構成パラメータとき裂分布・構造との相関関係について検討し、地下情報を推定するための相関関係式を提案している。これは実用上有益な知見である。

第4章では、物質移動挙動について空間的拡張を図る方法論について検討を行っている。具体的には、特定の間隔を有する坑井間で得られたトレーサ応答に対して、fADE モデルを活用することにより異なる坑井間距離に対するトレーサ応答を推定するための方法論を提案している。また、数値シミュレーション結果との比較により提案した方法の妥当性を示すとともに、本法の適用条件について検討している。これは、貴重な知見である。

第5章では、断裂型貯留層における熱移動挙動を評価・推定することを目的とし、非整数階微分に基づく複雑熱移動方程式 (fhTE) を提案している。本 fhTE モデルを用いて、還元に伴う生産井における温度変化の実フィールドデータをよく表現できることを示している。これは独創的な成果である。

第6章では、第5章で導出した fhTE モデルを構成する fhTE 構成パラメータと fADE 構成パラメータの関係に関して、逸水層を有する均質貯留層モデルならびに不均質貯留層モデルについて数値シミュレーションを用いて検討することにより、トレーサ応答から抽熱挙動を推定するための方法論を提案するとともに、適用条件について検討している。これは還元条件の最適化に役立てることができるなど、実用上有意義な知見である。

第7章は結論である。

以上要するに本論文は、非整数階微分を利用した物質・熱移動数理モデルを開発し、その工学応用に関する提案を行ったものであり、環境科学ならびに貯留層工学の発展に寄与するところが少なくない。

よって、本論文は博士 (学術) の学位論文として合格と認める。